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Concrete in sulphate-bearing soils and groundwaters

This Digest discusses the factors responsible for sulphate attack on concrete below ground level, and recommends what can be done, by suitable selection of cement type and concrete quality, to resist attack by naturally-occurring sulphates.

Digest 90 is now withdrawn.

Factors influencing attack

Aqueous solutions of sulphates attack the set cement in concrete, the chemical reactions occurring depending upon the kind of sulphate present and the nature of the cement. The rate of attack depends greatly on the permeability of the concrete. The factors influencing attack are:

(1) the amount and nature of the sulphate present;
(2) the level of the water table and its seasonal variation;
(3) the form of construction;
(4) the type and quality of the concrete.

If sulphate conditions cannot be prevented from reaching the structure, the only defence against attack lies in the control of the fourth factor; it cannot be too strongly emphasised that fully compacted concrete of low permeability must be used.

Occurrence of sulphates Sulphates occur mainly in strata of London Clay, Lower Lias, Oxford Clay, Kimmeridge Clay and Keuper Marl. The most abundant salts are:

calcium sulphate (gypsum or selenite)
magnesium sulphate (Epsom salt)
sodium sulphate (Glauber's salt).

Sulphuric acid and sulphates in acid solution occur much less often, for example, near colliery tips, in marshy country and where pyrite in the soil is being slowly oxidized.

Sulphates are sometimes present in materials such as colliery shale used as fill beneath solid concrete ground floors. Moisture from the ground carries the salts to the underside of the concrete, which they attack, leading to expansion and cracking of the floor and the surrounding structure.

Brick rubble, particularly with adhering plaster, ashes and some industrial wastes, are potential sources of damage by sulphate attack.

The solubilities of the salts mentioned—expressed as grams of sulphur trioxide (SO_3) per litre of solution—vary considerably. That of calcium sulphate is only 1·2 g (SO_3) per litre, compared with about 150 and 200 times this value for magnesium and sodium sulphates respectively. The SO_3 content of groundwaters therefore gives an indication that one or both of the latter sulphates may be present.

Movement of groundwater Sulphates can only continue to reach concrete by movement of their solutions in water. Thus concrete which is wholly and permanently above the water table is unlikely to be attacked, even though capillarity in the subsoil may cause some migration of salts to zones above the water table. Below the table, however, movement of water may replenish the sulphates removed by reaction with concrete, thereby maintaining the attack. Movements may be vertical or horizontal, depending on seasonal variations in rainfall and on the geology of the site and its environs. A low sulphate content in the soil does not eliminate the possibility of sulphate attack, since groundwater may flow from adjacent areas, particularly if the soil has been disturbed, e.g. by laying pipes.

Form of construction Given the same concrete quality and corrosive conditions, massive forms of construction will, as expected, deteriorate less quickly than thin sections. Special considerations apply to piles, since if the surface skin of concrete is attacked there could be changes in the friction on the pile shaft. Precast piles have advantages over those cast *in situ;* concrete quality—in particular compaction—is more easily controlled, since placing is less difficult (*see* Digest 95).

In basement structures, retaining walls, or culverts, for example, the concrete may have to resist strong lateral water pressure on one side only. This favours both water penetration and concentration of salts on the other side if evaporation of water from that side can occur. Similarly, partly buried concrete may draw up sulphates in solution from beneath by a combination of capillarity and evaporation at the exposed surfaces.

At first sight precast concrete pipes may appear rather more vulnerable to attack than other forms of concrete; they are thin in section and may be subjected to water pressure from one side only. Against this, however, is the fact that the concrete quality is usually high, to satisfy BS 556, and, providing the appropriate cement is used, this is the best safeguard against attack. (The internal corrosion of concrete pipes by sulphate salts in the effluent is discussed in Note No. 6: 1959 by the Water Pollution Research Laboratory).

Type and quality of concrete Concrete of low permeability is essential to resist sulphate attack; hence the concrete must be fully compacted. The mix must be so designed that it has sufficient workability to allow full compaction and yet has a free water/cement ratio no greater than that specified for the particular soil conditions. 'Free' water is the total weight of water in the concrete less that absorbed by the aggregate. (A method of measuring water absorption of aggregates is given in BS 812, Section 4).

Where sulphates are present, the mix should be designed to have a cement content not less than, and a free water/cement ratio not greater than, the values specified in Table 1 as appropriate to the severity of the conditions and the type of cement. For a particular situation, the cement content may have to be greater than the minimum specified in the table, so as to achieve the required workability within the limits of the maximum free water/cement ratio. This is particularly so for *in situ* concrete piles where the overriding consideration is to ensure complete compaction and therefore structural integrity of the pile; in this case, the mix must be designed to produce a highly workable but cohesive concrete. Admixtures for concrete such as air-entraining or water-reducing agents may give some limited improvement in sulphate resistance. Admixtures containing workability aids improve compaction and allow the use of lower water/cement ratios, but those containing calcium chloride are not recommended.

All precast units and any type of concrete using supersulphated cement require particular care during the initial curing period, so as to ensure minimum permeability and a hard surface.

Types of cement

In concrete prepared from ordinary or rapid-hardening **Portland cement** (BS 12) one reaction which occurs in sulphate solutions is with the hydrates formed from any tricalcium aluminate in the cement. Another involves the calcium hydroxide released during hydration. These reactions lead to a considerable expansion in the cement, finally resulting in the breakdown of the concrete. A considerable resistance to sulphate attack is obtained when the tricalcium aluminate content of the cement is kept low. Portland cements complying with BS 12 usually contain a significant proportion of tricalcium aluminate, but in **sulphate-resisting Portland cement** complying with BS 4027 the amount is limited to 3·5 per cent.

The resistance of concrete made with **supersulphated cement** (BS 4248) to attack by sulphates over the range of concentrations commonly encountered in groundwaters is similar to that of sulphate-resisting Portland cement. This cement is not currently produced in the UK but it has been found that good quality concrete made with it has an acceptable life in mildly acid conditions. Laboratory tests indicate that when immersed in strong magnesium sulphate solution (up to 3·5 per cent SO_3) concrete samples prepared from supersulphated cement lose strength more quickly than those prepared from sulphate-resisting Portland cement. In strong sodium sulphate solution, the current evidence is divided but, on balance, the relative resistances appear to be reversed.

The sulphate resistance of cements based on mixtures of granulated blastfurnace slag and Portland cement clinker increases with the proportion of slag. In addition to factory-produced cements, ground granulated blastfurnace slag is available for introduction at the mixer. BS 146 for **Portland-blastfurnace cement** does not set a minimum level for slag content and this cement is therefore classified with ordinary Portland cement. BS 4246 for **low heat Portland-blastfurnace cement** specifies a minimum slag content of 50 per cent which is probably less than is required for any substantial improvement in sulphate resistance over ordinary Portland cement but until the result of long-term tests are available there is little UK data on which to base precise recommendations.

The inclusion of pozzolanas improves the sulphate resistance of ordinary Portland cement concretes. Selected and classified pulverised-fuel ashes with good pozzolanic properties are available in the UK but here again the results of long-term tests are awaited.

Table 1 Requirements for concrete exposed to sulphate attack

Class	Concentration of sulphates expressed as SO_3			Type of cement	Requirements for dense, fully compacted concrete made with aggregates meeting the requirements of BS 882 or BS 1047			
	In soil		In groundwater		Minimum cement content			Maximum free water/cement ratio
	Total SO_3	SO_3 in 2:1 water:soil extract			Nominal maximum size of aggregate			
					40 mm	20 mm	10 mm	
	%	*g/litre*	*parts per 100 000*		*kg/m³*	*kg/m³*	*kg/m³*	
1	less than 0·2	—	less than 30	Ordinary Portland or Portland-blastfurnace	240	280	330	0·55
2	0·2–0·5	—	30–120	Ordinary Portland or Portland-blastfurnace	290	330	380	0·50
				Sulphate-resisting Portland	240	280	330	0·55
				Supersulphated	270	310	360	0·50
3	0·5–1·0	1·9–3·1	120–250	Sulphate-resisting Portland or supersulphated	290	330	380	0·50
4	1·0–2·0	3·1–5·6	250–500	Sulphate-resisting Portland or supersulphated	330	370	420	0·45
5	over 2	over 5·6	over 500	As for Class 4, but with the addition of adequate protective coatings of inert material such as asphalt or bituminous emulsions reinforced with fibreglass membranes				

Notes

This table applies only to concrete made with aggregates complying with the requirements of BS 882 or BS 1047 placed in near-neutral groundwaters of pH 6 to pH 9, containing naturally occurring sulphates but not contaminants such as ammonium salts. Concrete prepared from ordinary Portland cement would not be recommended in acidic conditions (pH 6 or less); sulphate-resisting Portland cement is slightly more acid-resistant but no experience of large-scale use in these conditions is currently available. Supersulphated cement has given an acceptable life, provided that the concrete is dense and prepared with a free water/cement ratio of 0·40 or less, in mineral acids down to pH 3·5.

The cement contents given in Class 2 are the minima recommended by the manufacturers. For SO_3 contents near the upper limit of Class 2, cement contents above these minima are advised.

For severe conditions, eg thin sections, sections under hydrostatic pressure on one side only and sections partly immersed, consideration should be given to a further reduction of water/cement ratio and, if necessary, an increase in cement content to ensure the degree of workability needed for full compaction and thus minimum permeability.

Classification of sites and recommendations for concrete

For classification purposes sites have been divided into five categories of increasing severity, based on the sulphate contents of the soil and groundwater. The recommended type of cement and the minimum cement content for each of these classes are given in Table 1. It must be remembered that the divisions between the classes are somewhat arbitrarily drawn and that the recommendations are judgments based on present knowledge.

Sampling and analysis of soils and groundwaters

All reliable information about the site should be examined in assessing the need for extensive analysis of the soil. The information should include an estimate of the sulphate content of any groundwater samples obtained during site investigation. The main danger in classifying sites on the basis of groundwater analysis alone lies in the difficulty in obtaining samples that are not diluted with surface water.

Suitable soil samples may be obtained from the test boreholes made for engineering purposes. They should be taken at every 1–2 m and wherever an obvious change in stratum occurs. Economic considerations will govern the number of soil samples analysed. When the cost of analysis is low compared with the preparation and bulking of the sample it is preferable to analyse the samples separately. If, to save costs, samples are combined, this should only be done for samples from the same depth in different boreholes when the type of stratum is the same.

Sulphate contents of the groundwater can be determined by any suitable analytical method. Concentrations in the fourth column of Table 1 are customarily expressed as parts SO_3, per 100 000 parts of water, so that analytical figures expressed in grams of SO_3 per litre must be multiplied by 100. The total sulphate content of the soil may be obtained by extraction with hot dilute hydrochloric acid, and is expressed as the percentage of SO_3 per dry weight of soil. If the sulphate present in the soil is predominantly the calcium salt, its low solubility may result in the total sulphate content giving too severe a classification for the site. In cases where the total sulphate exceeds 0·5 per cent it is suggested that the water-soluble sulphate should be determined. The soluble sulphate salts can usually be extracted from the soil using twice the weight of water and expressed as grams of SO_3 per litre of water extract. Classification on this basis is given in column 3 of Table 1.

The detailed analytical procedures for these determinations are published in a BRE Current Paper*, together with the methods for the quantitative determination of the metallic ions present.

Interpretation of analytical results The results of all the individual chemical analyses should be available to the engineer to assist him in deciding on the precautions necessary. If classification is based solely on the analysis of groundwaters, it should correspond to the highest sulphate concentration recorded. If classification is based on the analysis of only a small number of soil samples and the results vary widely, it may be worth while to take further samples for analysis. When a larger number of results are available it is suggested that the site classification should be based on the mean of the highest 20 per cent of the results. When the soil samples have been combined before analysis the selection should be more stringent, and the mean of the highest 10 per cent of results is suggested.

British Standards referred to in the text

BS 12 *Portland cement (ordinary and rapid-hardening)* Part 2 : 1971 Metric units

BS 146 : 1958 *Portland blastfurnace cement*

BS 556 *Concrete cylindrical pipes and fittings including manholes, inspection chambers and street gullies* Part 2 : 1972 Metric units

BS 812 : 1967 *Methods of sampling and testing of mineral aggregates, sands and fillers*

BS 4027 *Sulphate-resisting Portland cement* Part 2 : 1972 Metric units

BS 4246 *Low heat Portland-blastfurnace cement* Part 2 : 1974 Metric units

BS 4248 : 1968 *Supersulphated cement*

*CP3/68 *Analysis of sulphate-bearing soils in which concrete is to be placed*. S. R. Bowden.

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